LA-UR- 03-7307

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Title: Detector Tests for a Prototype Compton Imager

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Submitted to: Poster session IEEE Nuclear Science Symposium
October 20-24, 2003, Doubletree Hotel, Hayden Complex, Portland, Oregon, USA

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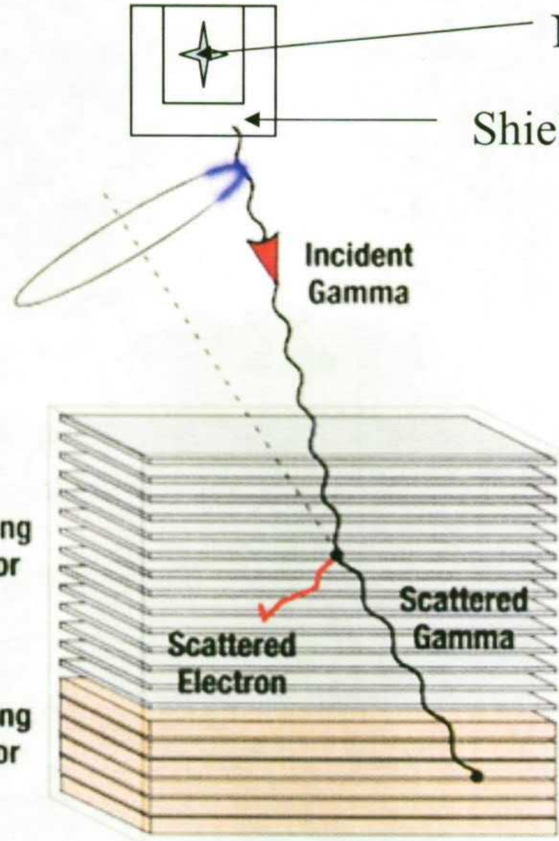
Motivation — Remote Sensing of Nuclear Materials

Detection using gamma-rays emitted by nuclear materials

- **Strategic:** develop technology to reduce the threat of weapons of mass destruction
  - Enhance capability by *detecting*, *localizing*, *characterizing*, and **averting** threats employing nuclear materials
  - Scan larger area from farther away
- **Scientific:** develop technology for groundbreaking observations of the solar system and the cosmos
  - Observe nuclear material emissions that unlock the secrets of nucleosynthesis, solar system formation, and planetary geology

Additional Motivation — Imaging Gammas From Neutron Activation

- Passive activation –shielding material identification

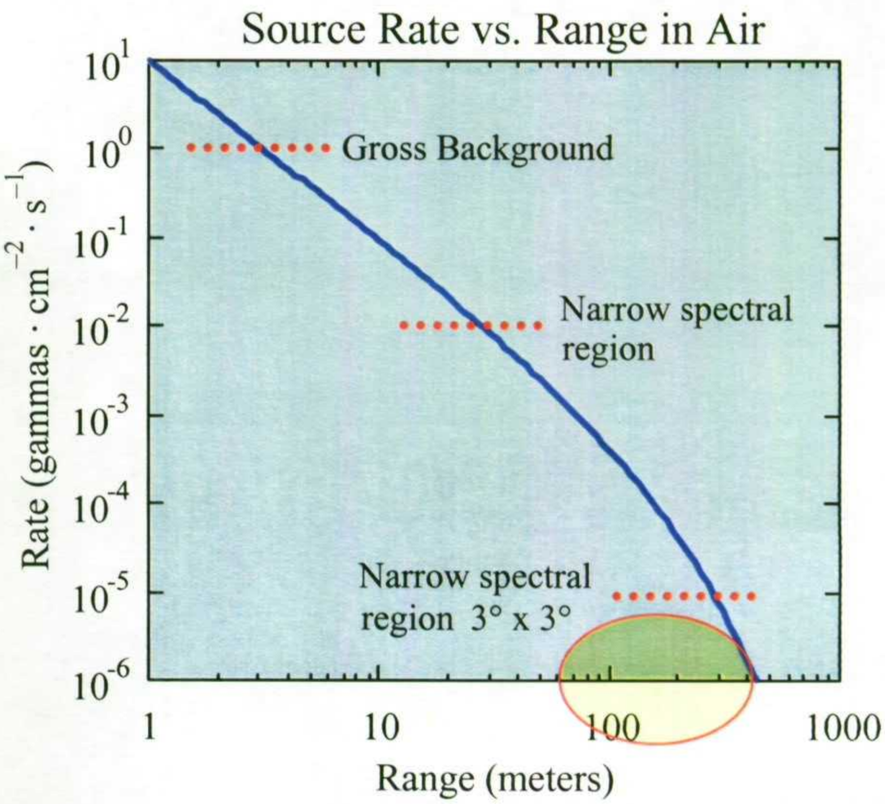


Challenges in Detecting Special Nuclear Materials (SNM)

- Gamma-ray emission from radioactive materials (e.G., HEU, Pu) provides a convenient means of passive detection. E ~ 0.15 – 3 MeV
- Terrestrial backgrounds are large
  - Background can include same spectral line as the source
    - Weak sources fade with distance and are easily confused with background (low signal to background ratio)
- Detection must be reported in 'real' time
  - Matter of several minutes
- Pinpointing a nuclear threat

Why Compton Imaging?

- Current detectors cannot distinguish background; range limited to a few meters
- <u>Imaging is the key</u>: reduces background; improves range and sensitivity

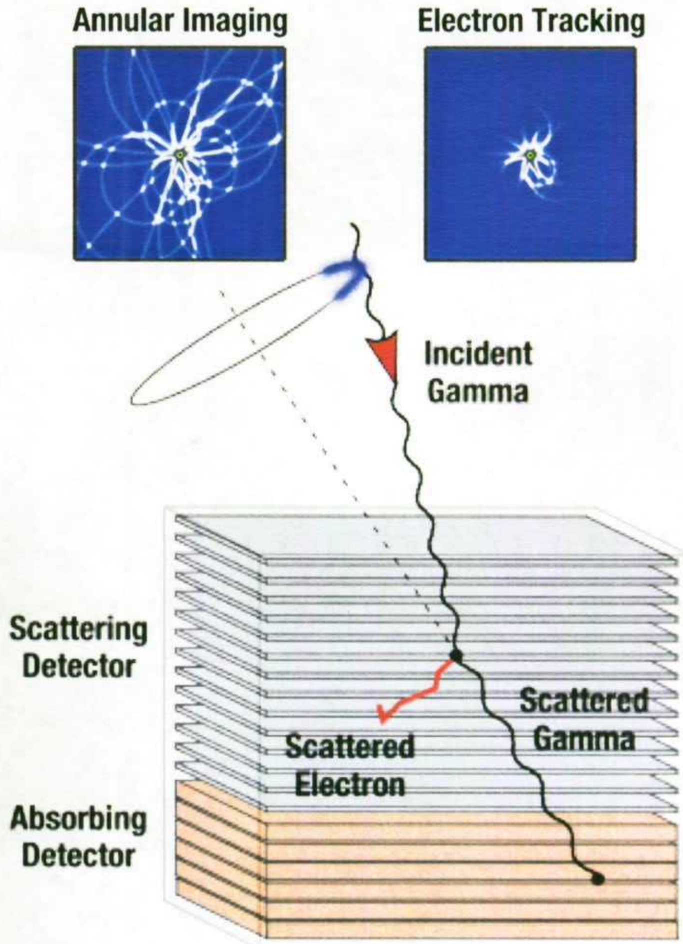


Why Compton Imaging?

- Continuously sensitive across a wide field of view
  - Mechanically collimated systems limit the field of view
  - Wide Compton scatter angle distribution provides imaging over a wide field of view
- Background rejection by angular sorting
  - Most background photons come from irrelevant directions
  - Multiplexed imaging systems mix signal information within the train of background
- Reasonable spectral resolution both on the tracker and imaging calorimeter
  - Spectral rejection of backgrounds

Technical Solution — Compton Imaging

- One clear solution — Compton imaging
- Kinematic reconstruction of gamma-ray direction, energy (and polarization)



<u>Advantages:</u>

(1) Background reduction (improved sensitivity)

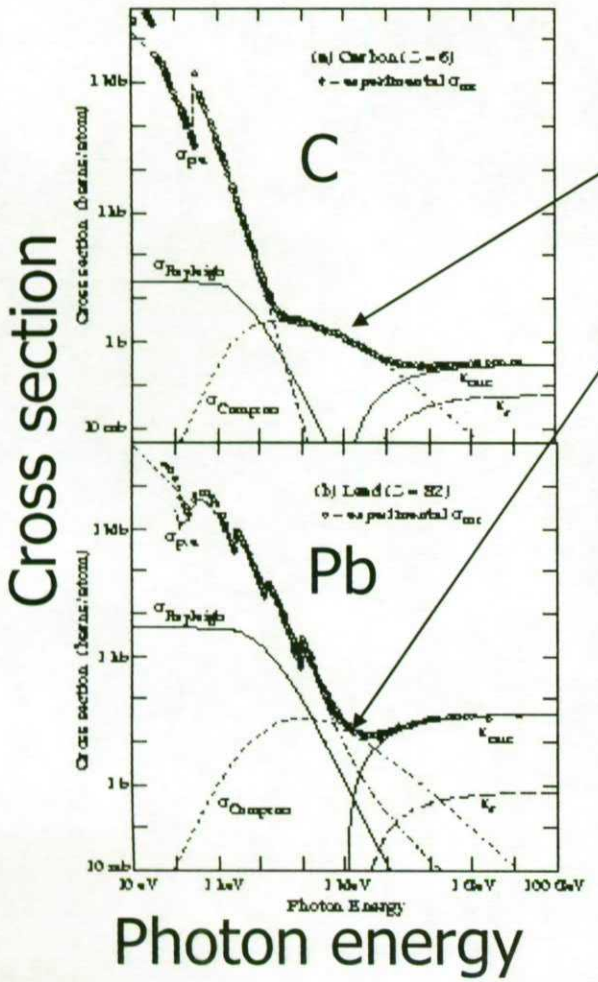
(2) Imaging/localization (3-D for close sources)

(3) Wide field of view (>few sr)

(4) Spectroscopy, isotope ID

Electron tracking further reduces background

Back of the Envelope Stuff



Compton scattering is the largest part of the cross section for ~1 MeV photons, especially for light elements

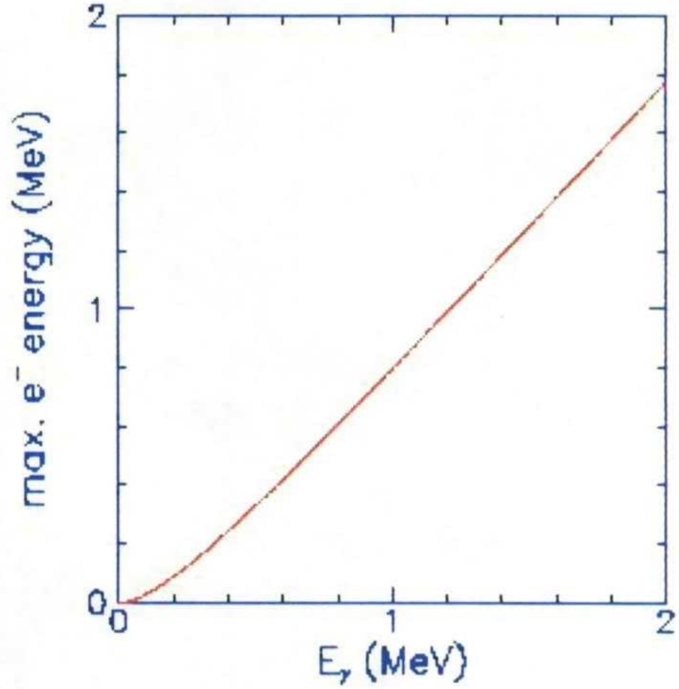
Probability for scattering of 1 MeV photon by:

300 μm Si	~ 0.44%
1 cm plastic scint.	~ 7%
100 cm air	~ 0.8%
1 mm iron	~ 5%

More Back of the Envelope

The scattered electron has an energy range from 0 up to the Compton edge:

There is a conflict between max efficiency (thicker detector) and measuring the electron angle (thin detector). One solution is to use many planes of thin detectors. Another is something like a TPC, which in a sense is many layers of thin detectors.



Requirements for Scattering Detectors

- **A low-z, low density material is required to minimize coulomb scattering so electrons can escape.**
- **For no electron tracking option.**
  - **Low Z detectors are still required to minimize Doppler ambiguities.**
    - **Effect is worse with Z of the scattering medium.**
- **Sufficient total thickness of active material to achieve reasonable detection efficiency.**
  - **Time projection chamber (TPC) may provide good electron tracking capability but may have to be impractically thick.**
  - **Xenon in TPC will add significant Doppler blur.**

Silicon (Si) stack is the best choice.

Requirements for Si Detectors

- AREA -- major concern. Several sq-m for an operational instrument. Scalability.

- READOUT -- tied to area. Minimize number of readout channels per unit detector area (while meeting position and energy resolution requirements) to achieve reasonable cost/power.

- NOISE (ENERGY RESOLUTION) -- reducing noise to ~1 keV improves performance. Much better than 1 keV does not yield much further improvement (Doppler limit).

- Position resolution -- ~0.5-1 mm in x and y (much better does not help performance, and usually means more readout channels).

Requirements for Si Detectors Continued

- THICKNESS -- 300 micron per detector is the maximum for tracking. Preferably thinner, but detectors must also be mechanically robust.

- DEADSPACE -- maximize ratio of active/passive mass on each detector layer. Also, detectors must be stackable, with minimal/no passive mass between layers (electronics on sides).

- OCCUPANCY -- low-rate applications, low probability for multiple hits in a ~few cm^2 area.

- RAD HARDNESS -- for space mission ~5-10 kRad dose over a 5-10 yr mission (depending on orbit). This should not be a driving consideration for development at this stage.

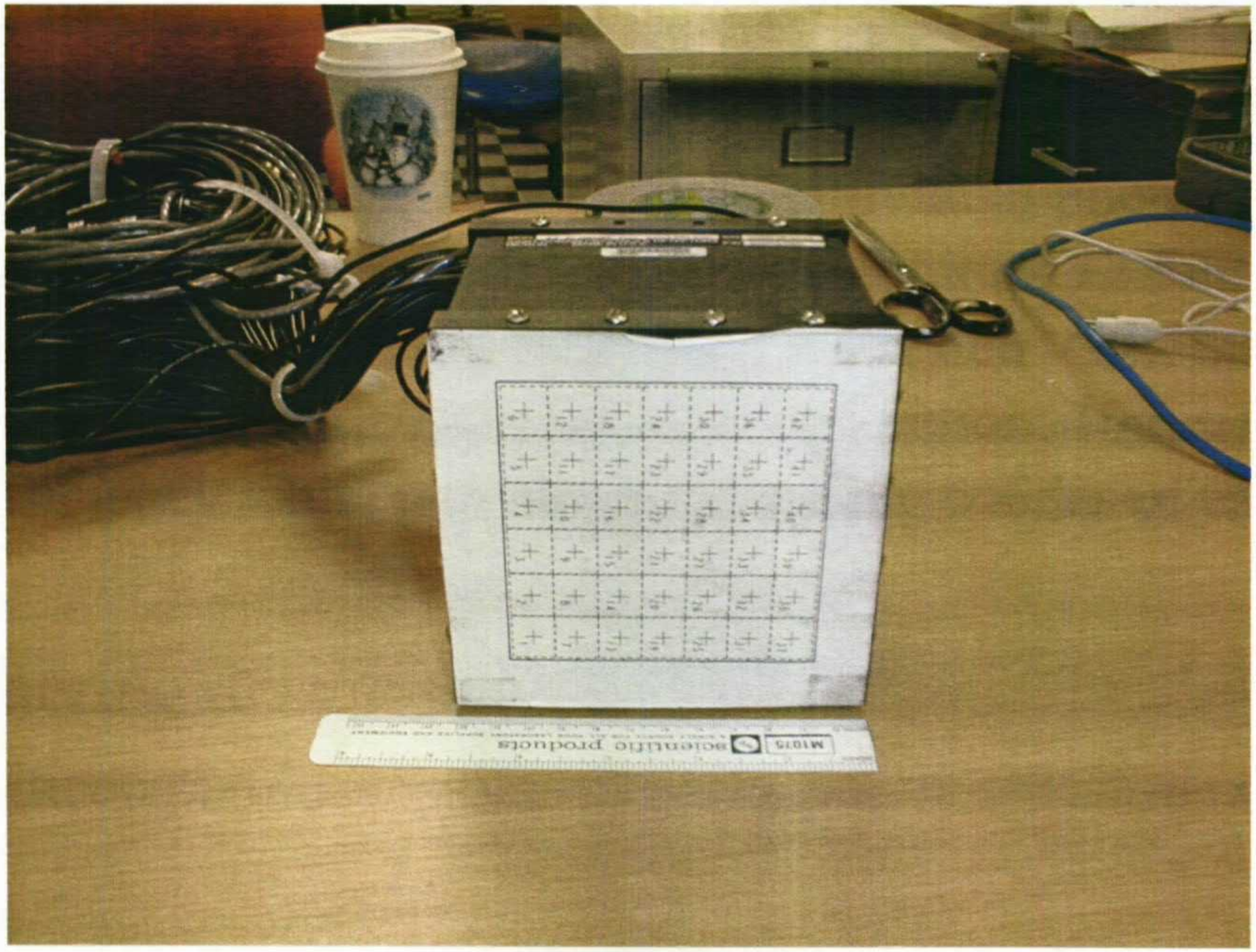
Large-area planar silicon detectors are available with integrated low noise electronics.

Construction of a Prototype

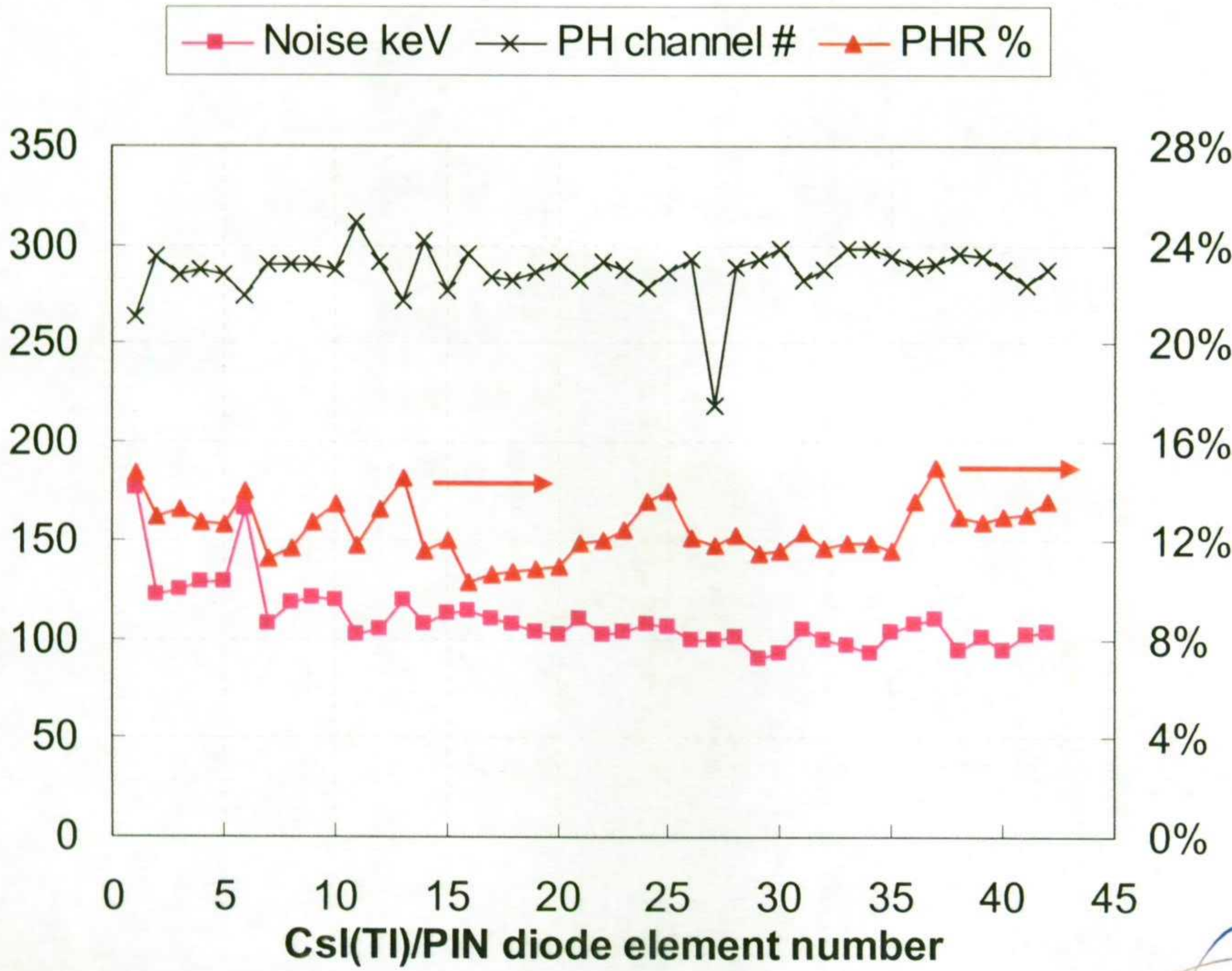
- CsI(Tl)/pin photodiode array for absorber.
  - (42 elements) 6 x 7 matrix with individual photodiodes attached to each crystal. Pixels - 14.3mm x 12.5mm to match the substrate size of each PD. Pitch - 14.5mm in "X" direction and 12.7mm in the "Y" direction. 10mm high-efficiency white reflector surrounding 5 sides of each pixel.

- Scattering detectors.
  - Silicon pixel detectors.

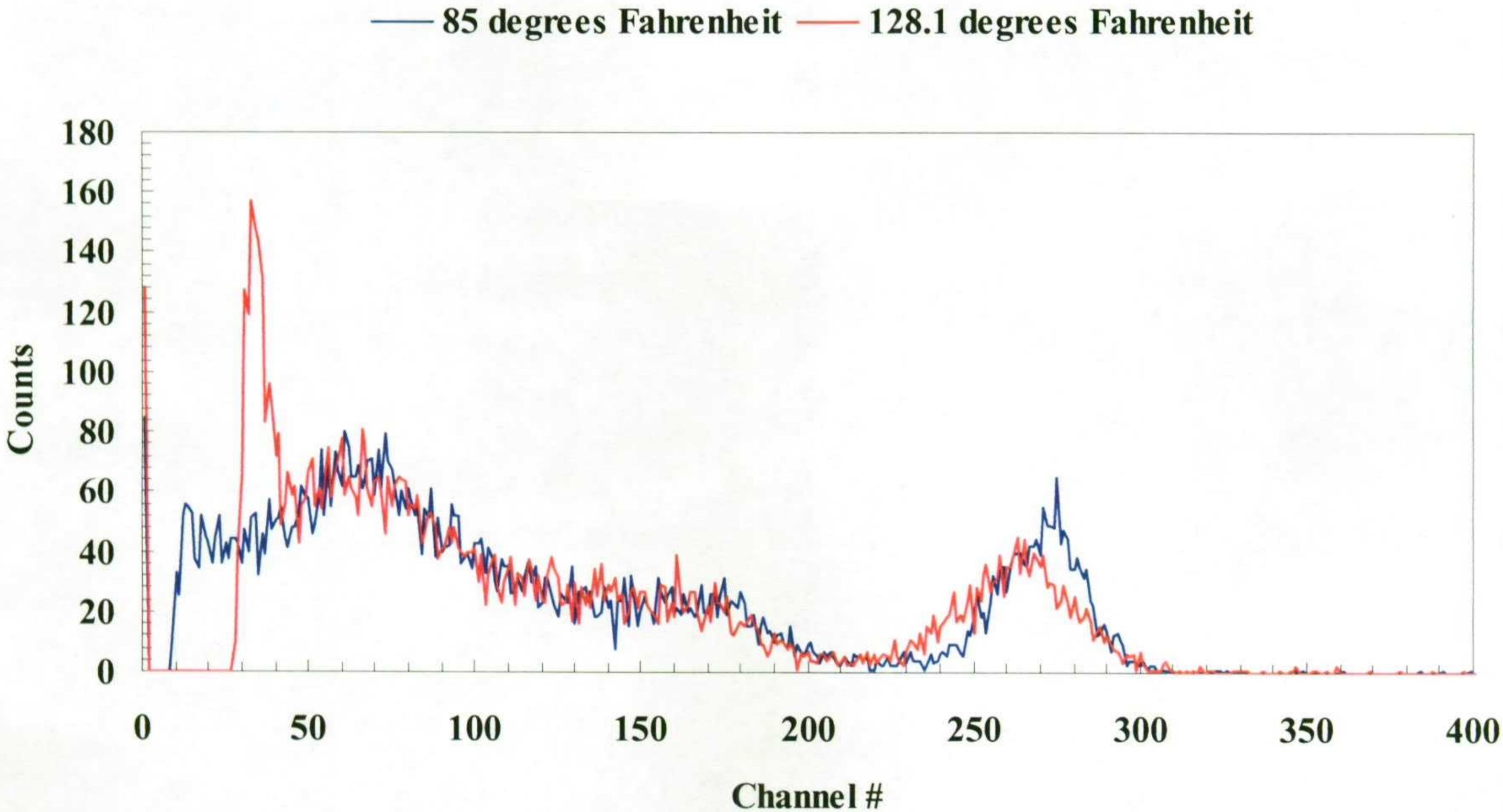
CsI(Tl)/pin PD Array



Characteristics: CsI(Tl)/pin PD Array

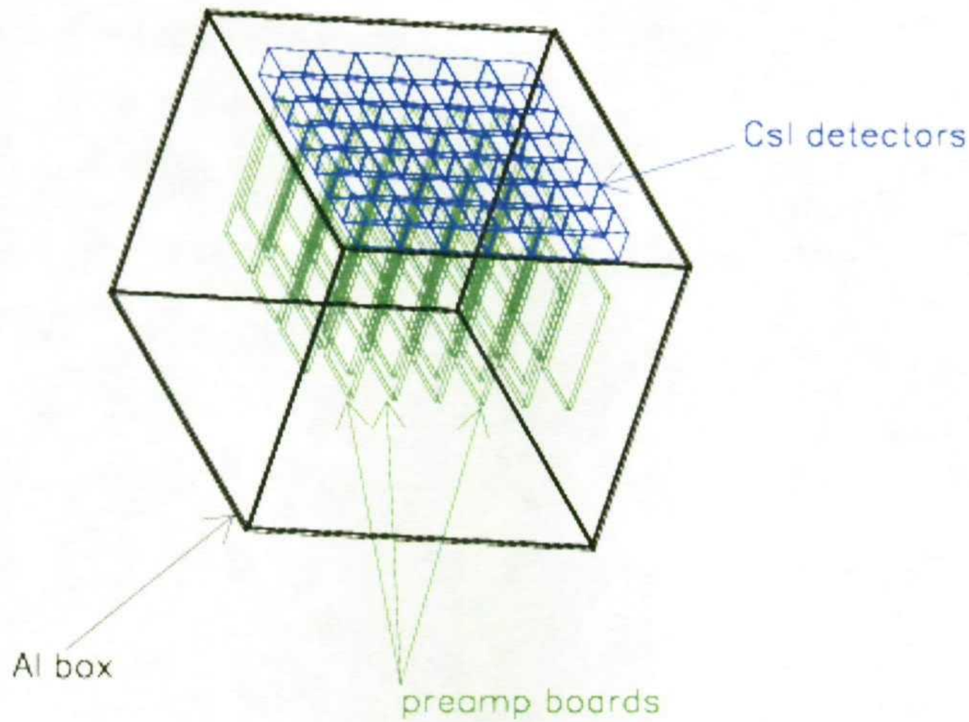


CsI(Tl)/pin PD: Temperature Effects

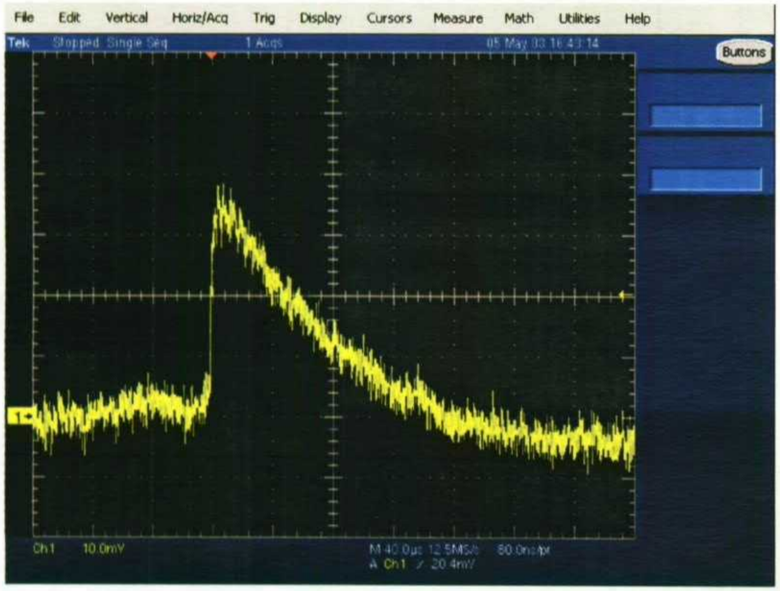


Simulations: CsI(Tl)/pin PD Array

Simulated version of CsI(Tl)/PIN PD array

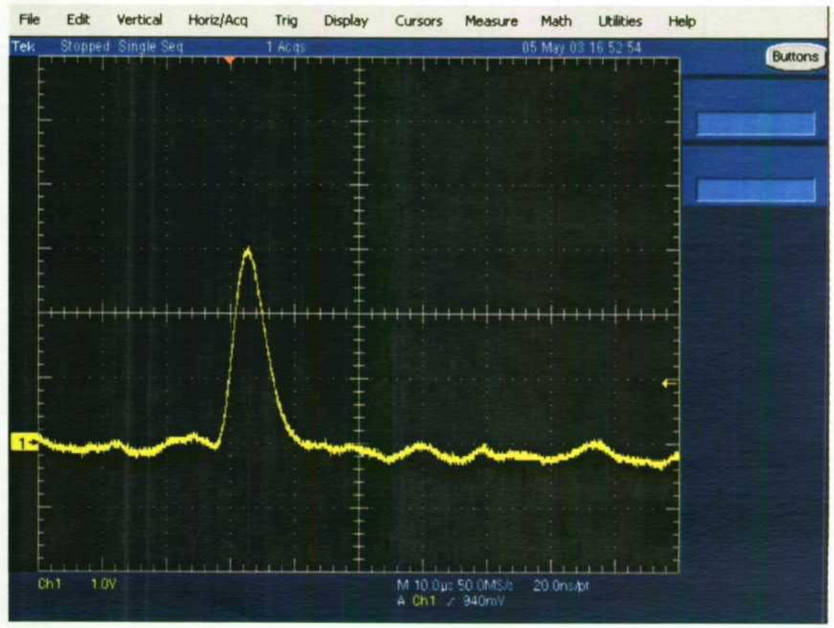


CsI(Tl)/pin PD Preamplifier Output



Scope shot of CsI preamp output, 40 microsec per division horizontal, 10 mV/division vertical

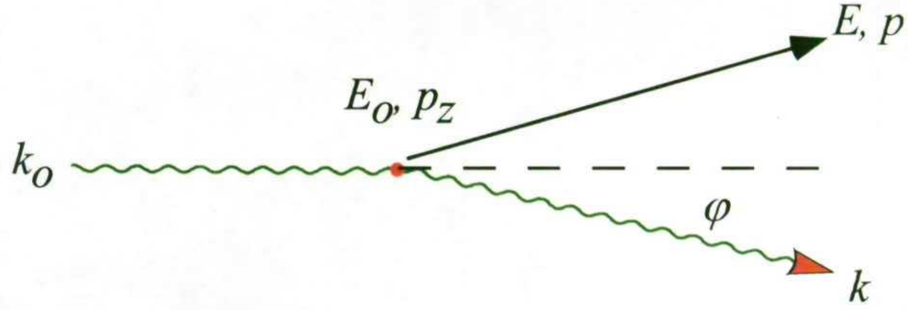
Scope shot of CsI output from spectroscopy amp – 10 microsec/div horizontal and 1 V/division vertical.



Doppler Broadening Physics & Effects

For free electron: $p_z = 0\,; E_o = m_o c^2$

$$k_{\text{free}} = \frac{k_o}{1 + \frac{k_o}{m_o c^2}(1 - \cos\varphi)}$$

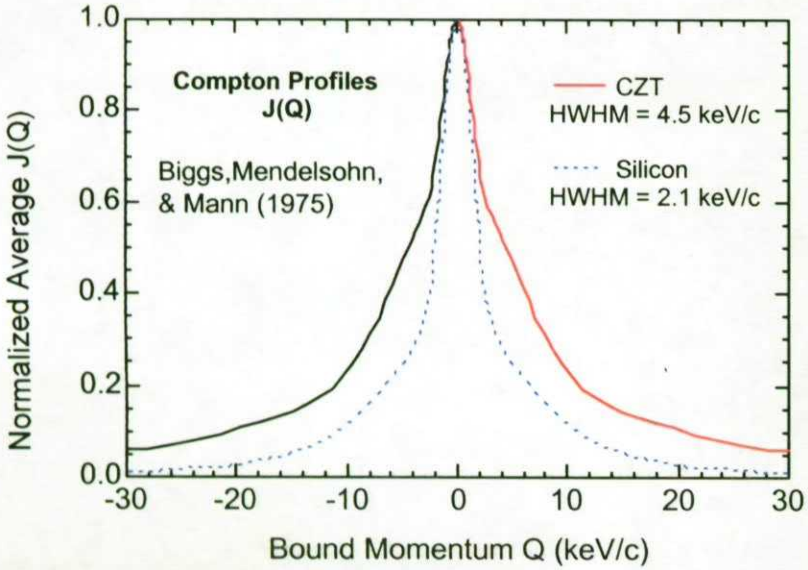


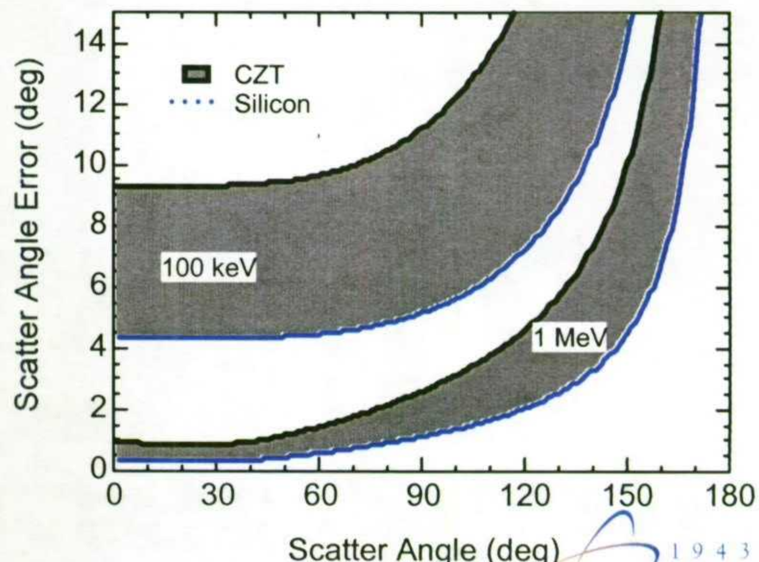
For bound atomic electron:

$$k = k_{\text{free}}\left(1 - \frac{p_z|\mathbf{k_o} - \mathbf{k}|}{mc^2 k_o}\right)$$

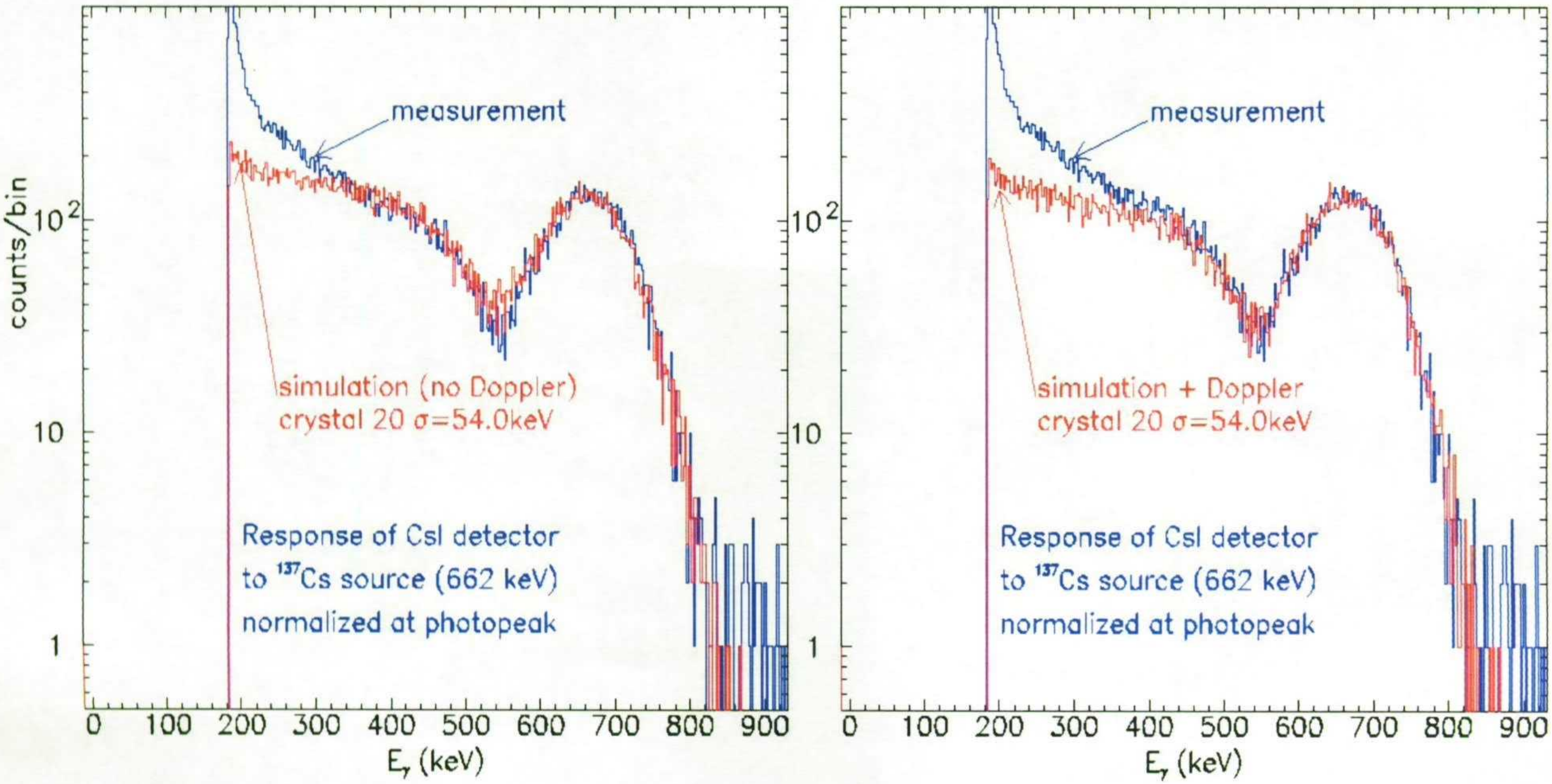
Doppler broadening error:

$$\Rightarrow \quad \Delta k = k - k_{\text{free}}; \quad \Delta\varphi = \varphi - \varphi_{\text{free}}$$





Comparison: Data and Simulations

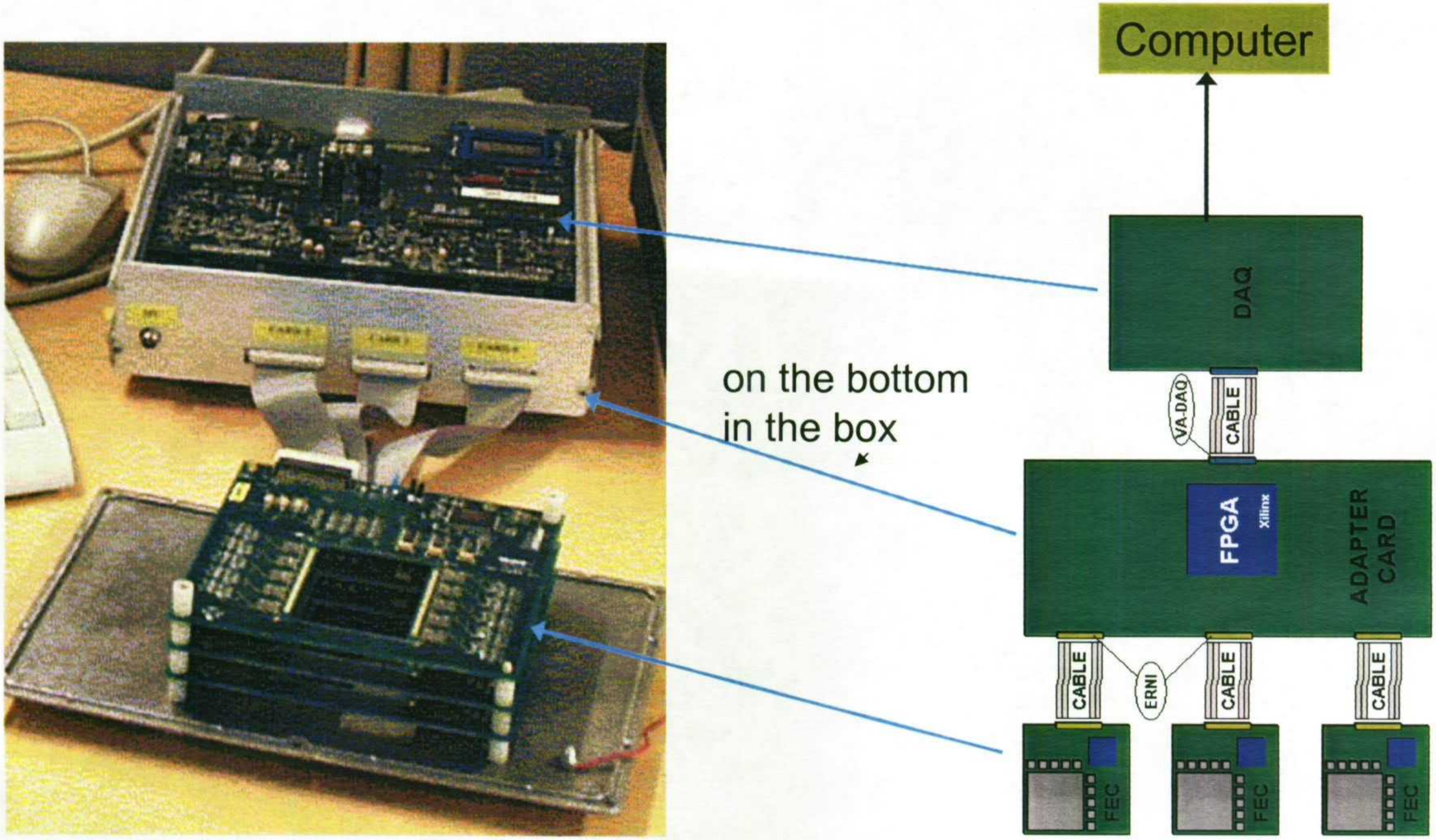


Front-end Electronics for Si Detectors

The system was built by IDE, a commercial company, based on our specifications and their custom ASICs.

- VA series of ASICs for the preamplifier.
- TA series of ASICs for the discriminator.
- Trigger on any channel in any pixel detector or a coincidence of all three.
- Custom boards designed and built by IDE for trigger, ADC's, readout control.
- Semi-custom readout hardware+software system ("VA-DAQ") based on LabVIEW.

Si Readout System



Si Pixel Detectors

SPD 58mm X 63mm

320 - 3mm X 3mm readout pads

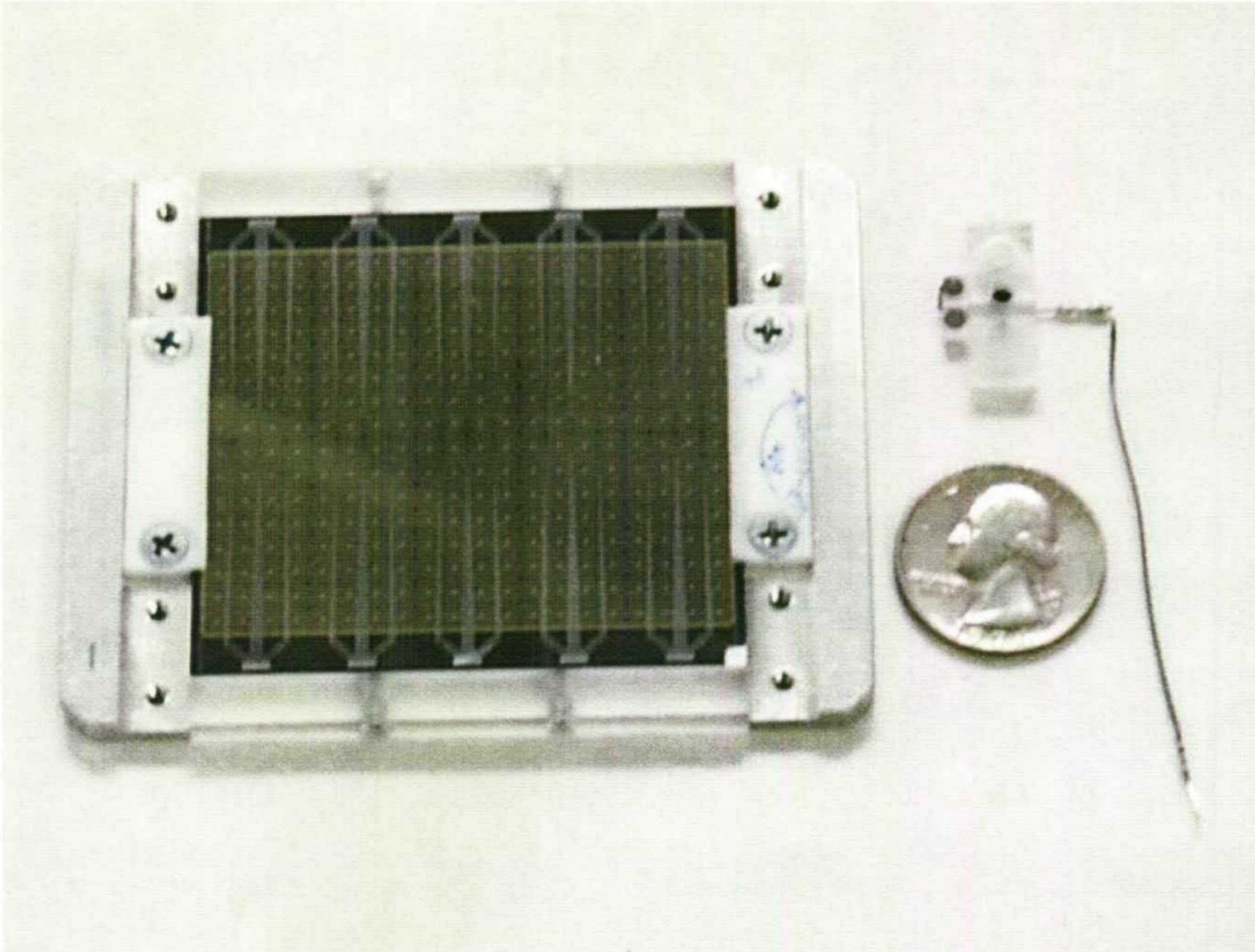
n+/n/p+ type substrate

16 X 20 grid pattern

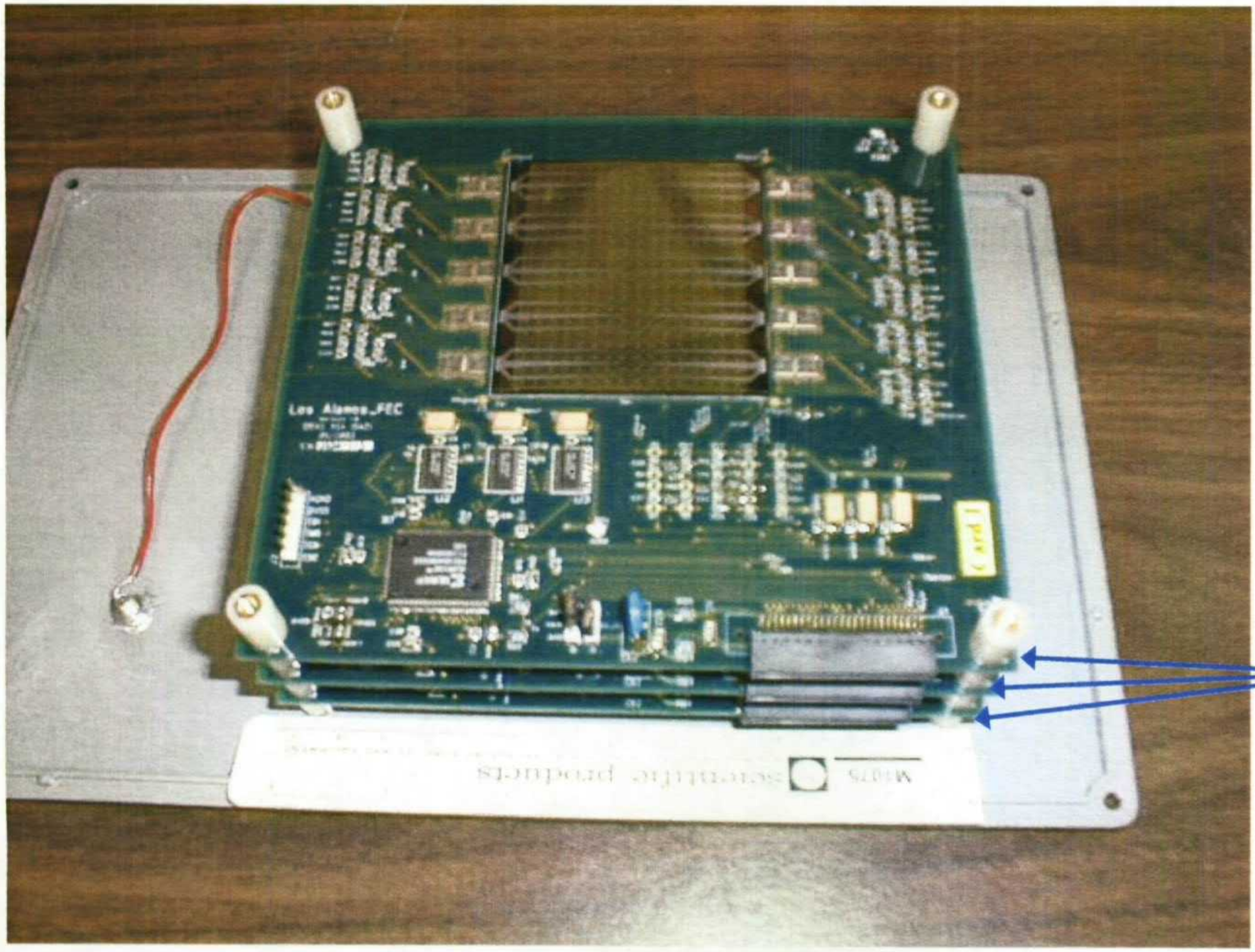
Individual bonding pads

270μm thick

Dr. Zheng Li of BNL

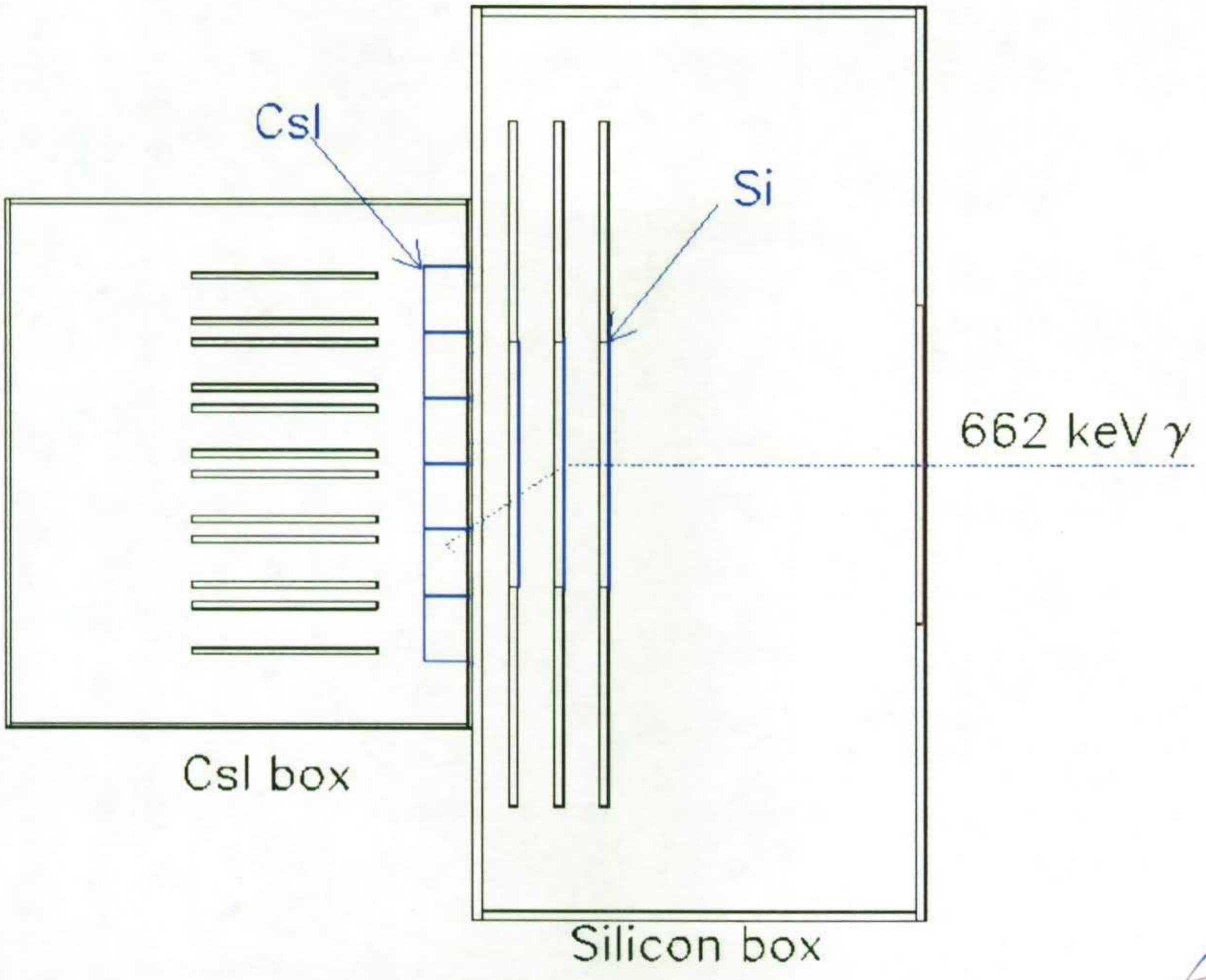


Si Detectors wirebonded to the Front-end Cards



3 front-end cards, 1 cm separation

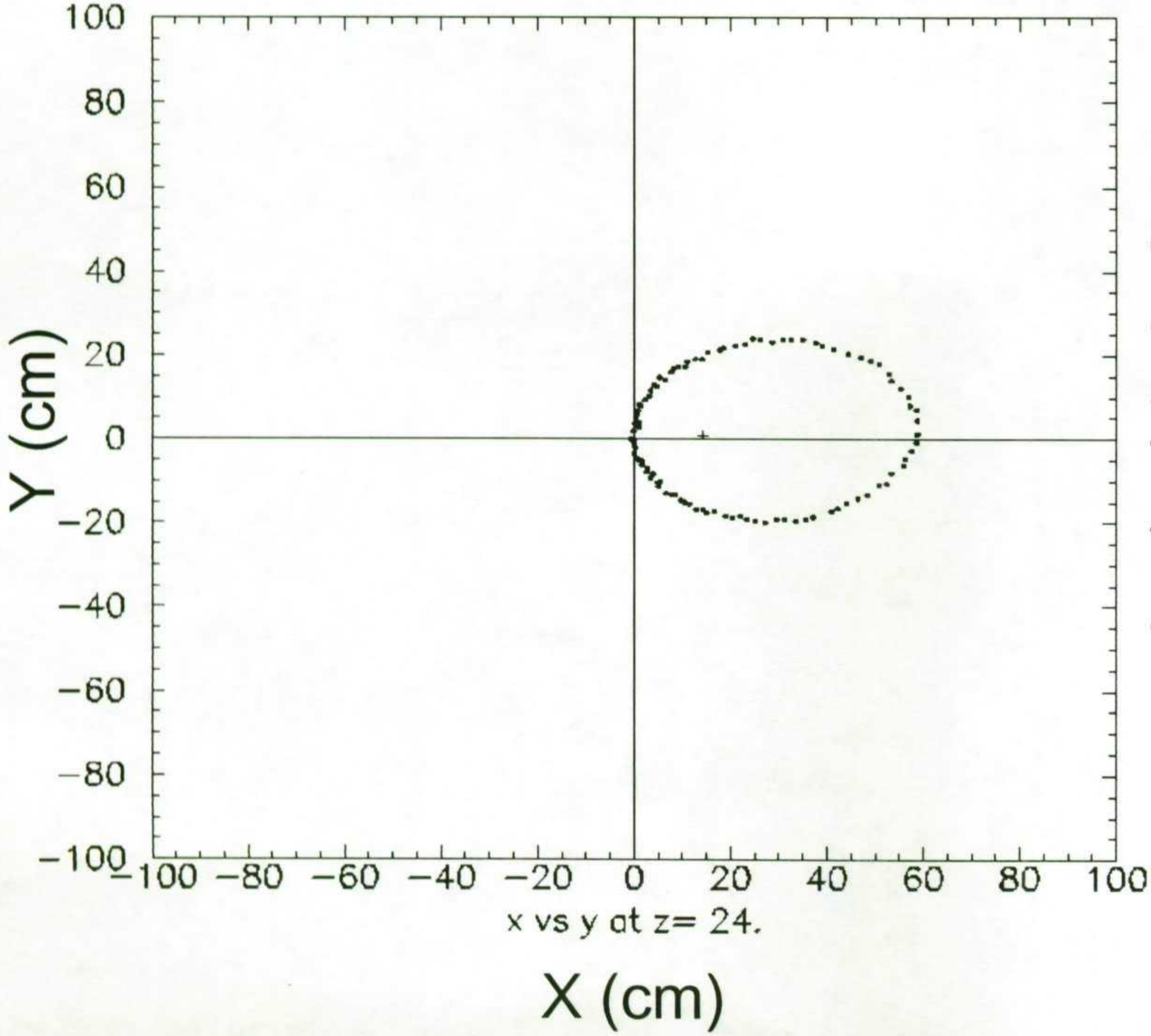
Top View of the Compton Imager (Simulation)



Reconstruction Algorithms

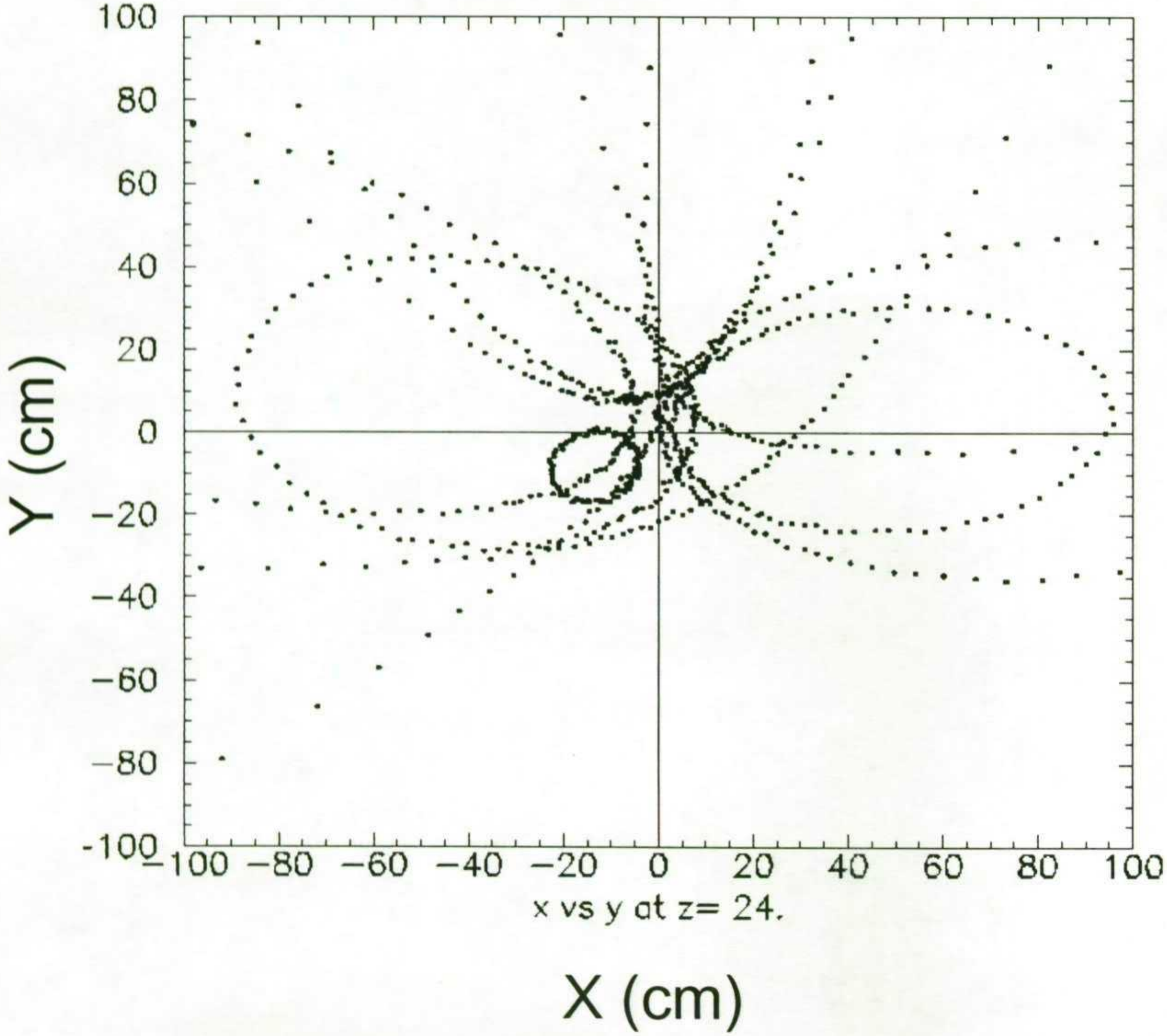
- Our first reconstruction algorithm treats every combination of 1 hit in the silicon detector and 1 hit in the CsI as a possible Compton scatter event.
- The cone corresponding to the Compton scatter event is projected onto both a set of planes fixed distances from the detector and onto a "theta-phi" plot histogram.
- The cone is approximated by 100 vectors at equally spaced values of "phi" around the cone which are projected to the planes.

A Sample Ring



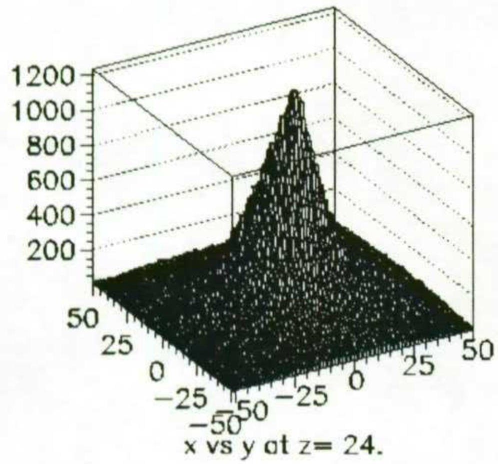
In this example, perfect position and energy resolution are assumed. The source is at x=y=0. The ring goes through this point as it should.

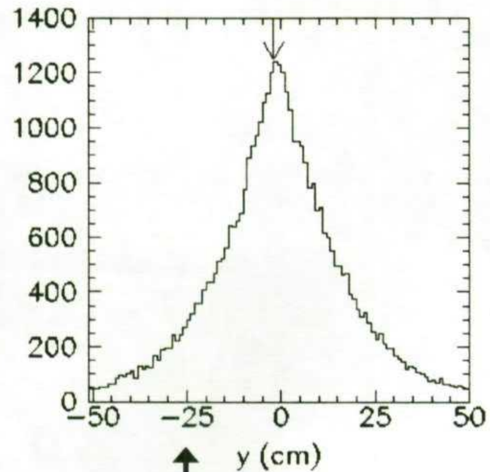
Rings From 10 Events



In this example, the real energy and position resolution of the Silicon and CsI are assumed. The source is still at x=y=0. Because of the finite resolution, most rings miss this point by ~5 cm.

Combining Many Events

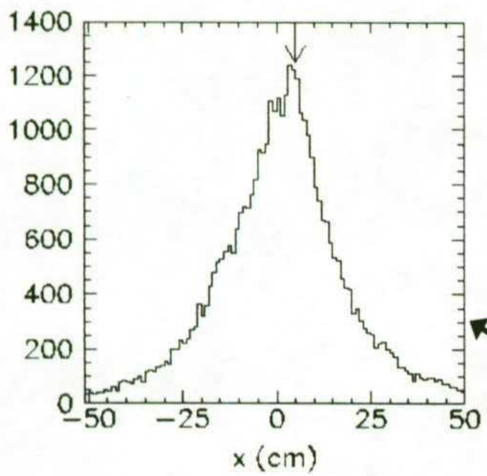




In this example, the source is at (x,y) = (5, -2 cm).

In the 2D histogram, the peak is actually at (3.5, -0.5 cm).

Cut along y direction at peak position



Cut along x direction at peak position

Summary

- Work is well on the way
  - Need back-end electronics
  - Solve CsI/pin PD noise problems
  - Maintain absorber array at constant temperature
  - Data acquisition system
  - Simulations
  - Reconstruction algorithms
  - Data with 'real' sources and background
  - Comparison between simulations and data